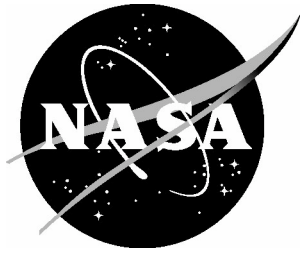


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The Influence of Model Complexity on the Impact Response of a Shuttle Leading-Edge Panel Finite Element Simulation

*Alan E. Stockwell
Lockheed Martin Space Operations
Langley Research Center, Hampton, Virginia*

March 2005

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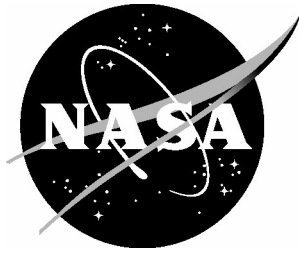
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*Alan E. Stockwell
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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

LS-DYNA simulations were conducted to study the influence of model complexity on the response of a typical Reinforced Carbon-Carbon (RCC) panel to a foam impact at a location approximately midway between the ribs. A structural model comprised of Panels 10, 11, and T-Seal 11 was chosen as the baseline model for the study. A simulation was conducted with foam striking Panel 10 at Location 4 at an alpha angle of 10 degrees, with an impact velocity of 1000 ft/sec. A second simulation was conducted after removing Panel 11 from the model, and a third simulation was conducted after removing both Panel 11 and T-Seal 11. All three simulations showed approximately the same response for Panel 10, and the simplified simulation model containing only Panel 10 was shown to be significantly less expensive to execute than the other two more complex models.

Introduction

Following the Space Shuttle Columbia disaster on February 1, 2003 and during the subsequent investigation by the Columbia Accident Investigation Board (CAIB), various teams from industry, academia, national laboratories, and NASA were requested by Johnson Space Center (JSC) Orbiter Engineering to apply “physics-based” analyses to characterize the expected damage to the shuttle thermal protection system (TPS) tile and Reinforced Carbon-Carbon (RCC) material, for high-speed foam impacts. The forensic evidence from the Columbia debris eventually led investigators to conclude that the breach to the shuttle TPS was caused by a large piece of External Tank (ET) foam that impacted and penetrated the lower portion of a left-wing leading-edge panel. As a result, NASA authorized a series of tests that were performed at Southwest Research Institute to characterize the impact response of the leading-edge RCC panels.

Recommendation 3.3-2 of the CAIB report [1] requests that NASA initiate a program to improve the impact resistance of the wing leading edge. The second part of the recommendation was to ...“determine the actual impact resistance of current materials and the effect of likely debris strikes.” For Return-to-Flight (RTF), a team consisting of personnel from NASA Glenn Research Center, NASA Langley Research Center, and Boeing Philadelphia was given the following task: to develop a validated finite element model of the shuttle wing leading edge capable of accurately predicting the threshold of damage from debris including foam, ice, and ablators for a variety of impact conditions. Since the CAIB report was released, the team has been developing finite element models of the RCC leading-edge panels; executing the models using LS-DYNA [2], a commercial nonlinear explicit transient dynamic finite element code; conducting detailed material characterization tests to obtain dynamic material property data; and, correlating the LS-DYNA analytical results with experimental data obtained from impacts tests onto RCC panels. Some of the early results of this research are described in References 3-7.

The purpose of this report is to describe LS-DYNA simulations that were conducted to study the influence of model complexity on the response of a typical RCC panel to a foam impact at a location approximately midway between the ribs. A structural model comprised of Panels 10, 11, and T-Seal 11 (see Figure 1) was chosen as the baseline model for the study. A simulation was conducted with foam

striking Panel 10 at Location 4 at an alpha angle of 10 degrees, with an impact velocity of 1000 ft/sec. A second simulation was conducted after removing Panel 11, and a third simulation was conducted after removing both Panel 11 and T-Seal 11. Thus the purpose of this analytical study was to determine the influence of adjacent structure on the dynamic response of Panel 10.

Model Description

The complete model, including the foam projectile, RCC Panels 10 and 11, and T-Seal 11, is shown in Figure 1, and model details are highlighted in Table 1. The panel models, developed by Boeing, were discretized using Belytchko-Tsay quadrilateral shell elements having nominal element edge lengths of 0.2 inches (see Figure 2). The panel models each consisted of 58 different regions or “parts.” Key parts are labeled in Figure 3. The quadrilateral shell elements representing the RCC panel midsection and ribs were assigned material type 58, designated MAT_LAMINATED_COMPOSITE_FABRIC, with the fibers in each layer oriented in the 0°/90° direction. Material properties for the models in this study were based on degraded, minimum-strength values. Prior testing of RCC material shows that it is much stiffer and stronger in compression than in tension, thus requiring a bimodular material model. Also, the stiffness and strength of flight-conditioned material is significantly lower than pristine RCC material. Consequently, the term ‘degraded’ refers to the fact that flight-conditioned material properties were used. RCC also exhibits considerable variability in material response and it is common to see a band or range of curves used to describe the tensile and/or compressive response, typically maximum, average, and minimum response curves.

The RCC Panel 10, Panel 11, and T-Seal models were supported at the bolts that fasten the panels/T-seals to the wing leading edge support structure. The bolts were represented using 0.1-in.-thick shell elements that were assigned rigid material properties using material type 20 MAT_RIGID. These elements were constrained from translational motion in the x-, y-, and z-directions using the BOUNDARY_PRESCRIBED_MOTION_RIGID card in LS-DYNA.

The finite element model of the BX-250 foam projectile had overall dimensions of 2.0 x 7.0 x 11.88-in. and was discretized using hexagonal solid elements having nominal element edge lengths of approximately 0.2 inches. The foam block weighed 0.23 lb. The material properties of the BX-250 foam were represented using material type 83 MAT_FU_CHANG_FOAM with MAT_ADD_EROSION in LS-DYNA. The erosion card is added to allow for element failure in the foam constitutive model. The experimental foam material responses were input into the model using the DEFINE_CURVE command in LS-DYNA. The responses were obtained from the testing of foam components performed at NASA Glenn Research Center. These tests were conducted to determine the influence of strain rate on the compressive response of the foam material. Results for three strain rates, 0.00167 s^{-1} , 25 s^{-1} , and 429 s^{-1} are plotted in Figure 4. The material response data are plotted only up to 200-psi stress to aid in visualization of the differences caused by strain rate; however, the stress data at strain values approaching 1 are 70,000 psi and higher. The response of the BX-250 foam, shown in Figure 4, is typical of other foam responses in that it exhibits a linear response at low strains, and as crushing begins a “knee” occurs in the response. Then, as stable crushing continues, the stress increases gradually until the cells within the foam begin to compact. As compaction initiates and continues, the stress increases dramatically for relatively small increases in strain. As shown in Figure 4, the influence of strain rate is to increase the stress at which the knee occurs, to increase the stress during stable crushing, and to lower the strain at which compaction begins. A tensile failure stress of 86-psi was assigned to the foam, based on tensile test data, as shown in Figure 4.

All of the nodes used to create the foam projectile were assigned an initial velocity of 1000 ft/s (12,000 in/s) along a vector that is parallel to the long edge of the foam block (see Figure 2). The velocity vector was determined by rotating a vector along the shuttle's longitudinal (x) axis through an angle of 10 degrees about the y axis ($\alpha = 10^\circ$). A *CONTACT_AUTOMATIC_NODES_TO_SURFACE_MPP was specified between the panel midsection and the foam in the model. For this contact, the panel midsection was designated the master surface, and the foam nodes were specified as the slave entity. A *CONTACT_AUTOMATIC_NODES_TO_SURFACE was specified for the RCC-to-RCC contact (i.e., T-Seal-to-panel contact).

Simulation Results

Three simulations were run to assess the influence of adjacent structure on the response of Panel 10 to a foam impact at Location 4. The three models are shown in Figure 5. The first model is the baseline model that included Panel 10, T-Seal 11, and Panel 11. All three structural components were fixed at the attachment bolt locations, and forces were transmitted between components by means of surface-to-surface contacts. The second model included Panel 10 and T-Seal 11 but did not include Panel 11. The third model included only Panel 10. The purpose of this study was to determine whether including the models of T-Seal 11 and Panel 11 would significantly affect the response predictions. This study was motivated by a desire to substantially reduce the computational expense for executing the hundreds of simulations required to fully characterize the impact damage threshold of the shuttle wing leading edge panels.

The results of the analytical study are presented as contour plots of resultant panel deflections and time history plots of internal and kinetic energy of the panel midsection, the resultant contact force response, and the kinetic and hourglass energy of the foam. Note that simulation times for key events are approximate, since results were output to the database at discrete intervals of 0.0002 seconds. It should also be noted that only one impact location was considered in this study. Foam strikes at other locations could yield much different results, especially for impacts close to a T-Seal.

Deformations

Selected deformation plots are shown in Figure 6 for the baseline model (Panels 10, 11 and T-Seal 11). The first evidence of RCC failure is seen at about 0.0012 seconds. This failure appears as a small vertical crack formed by the erosion of eight elements (Note that the foam obscures the crack at $t=0.0012$ sec in Figure 6). As the vertical crack grows, a second horizontal crack branches off at about the mid length of the vertical crack at time $t = 0.0016$ sec. At $t = 0.003$ seconds the crack branches again, running vertically downward from the tip of the horizontal crack. This appears to be the maximum damage sustained by the panel, as shown in the final deformation state of the simulation at $t=0.004$ seconds.

Strain

A strain comparison of the three simulations is presented in Figure 7. A time sequence is shown with snapshots of the maximum principal strain contours at 0.0012, 0.0016, 0.003 and 0.004 seconds. The maximum principal strain is computed by searching through all plies for the maximum value of the first principal strain for each element. Contours are drawn based on the computed maxima, which may occur in different plies for different elements. Contours are computed for maximum history variables in a similar manner. Only Panel 10 is shown in the plots, since it is the area of interest in the study. The panel is oriented so that the rib that is in contact with T-Seal 11 is visible. The figure shows that the strain

distributions for the three simulations match closely. Note that a strain of 0.005 was chosen as the reference strain for comparing the contour levels. Some strains plotted may actually exceed this chosen maximum value.

Damage Parameters

The LS-DYNA Mat 58 representation of the RCC includes a progressive failure feature that uses three non-physical failure indices referred to as “history variables.” These three parameters indicate the degree of failure on a ply-by-ply basis for the two in-plane directions as well as shear. A contour plot comparison of history variable 1 is shown in Figure 8 for the three models. Again these plots show that there is little significant difference in the predicted damage distribution for the three simulations.

Energies

Panel and foam energies are shown in Figures 9 and 10 respectively for the model that included only Panel 10. Energies for the other two models are not shown, because the plots are nearly indistinguishable.

Contact Forces

There are three contacts defined in the baseline model (Panels 10, 11 and T-Seal 11). They are 1) the foam/Panel 10 contact, 2) the contact between Panel 10 and T-Seal 11, and 3) the contact between T-Seal 11 and Panel 11. Time histories of the three contact forces are plotted in Figure 11 for the baseline model. Two more curves are also included on this chart. They are the foam/Panel 10 contact forces for the remaining two models. These curves demonstrate the nearly identical contact forces between the foam and Panel 10 in all three simulations. The calculated impulse for all three simulations was 4.2 lb-sec. It is also clear from the curves in Figure 11 that the further downstream the structure is from the impact site, the lower the magnitude of the contact force between adjacent components.

Response of Downstream Components

Panel 10 experienced strains that were high enough to lead to structural failure; however Panel 11 and T-Seal 11 did not see nearly the same level of strains and therefore neither component was damaged. The maximum principal strains in Panel 11 and T-Seal 11, are shown in Figures 12 and 13 respectively. Most strains are very low, with the exception of a few “hot spots.” The maximum principal strain in the T-Seal was 1363 microstrain and the maximum principal strain in Panel 11 was 458 microstrain. As expected, both strains are well below the material failure limits.

Effect of Including Panel 11

A plot of the contact force between Panel 10 and T-Seal 11 is shown in Figure 14 for the two models that included the T-Seal. The force time histories are very close during the initial impact. The difference between the two curves is more noticeable in the post-impact response period but is still small compared to the magnitude of the forces.

Computational Effort

All simulations were run using the MPP (multiple processor) version of LS-DYNA. Two processors were used for the simplest model, and 4 processors were used for the two multi-component models. A

plot of computational effort for the three models is shown in Figure 15. The computational effort was defined as the product of the number of processors times the clock time in hours. It was then nondimensionalized by dividing all quantities by the value computed for the baseline model. There is a 20 percent reduction in computational effort when Panel 11 is eliminated from the model, and there is a nearly 60 percent reduction in effort when the T-Seal is also removed. Factors affecting these differences are the number of elements, the requested output quantities, and the number and complexity of surface-to-surface contacts between adjacent structures and the computational overhead associated with using multiple processors.

Concluding Remarks

Three models of varying complexity were used in the simulation of an impact at Location 4 on Panel 10. The purpose of this study was to determine the amount of adjacent structure that would be required to accurately assess the effects of a foam block impacting a typical RCC panel. All three simulations showed approximately the same response for Panel 10. Further investigation of the responses of downstream components verified that the forces transmitted to the adjacent structure were not significant enough to affect the response of the impacted panel. It should be noted that only one impact location was considered in this study. Foam strikes at other locations could yield much different results, especially for impacts close to a T-Seal. A significant computational savings (nearly 60 percent) was achieved by simplifying the simulation model, without compromising the fidelity and accuracy of the analytical results.

References

1. Gehman, H. W., et al, "Columbia Accident Investigation Board," Report Volume 1, U. S. Government Printing Office, Washington, DC, August 2003.
2. Anon., "LS-DYNA Keyword User's Manual Volume I and II – Version 960," Livermore Software Technology Company, Livermore, CA, March 2001.
3. Carney, K., Melis, M., Fasanella, E., Lyle, K., and Gabrys, J.: "Material Modeling of Space Shuttle Leading Edge and External Tank Materials for Use in the Columbia Accident Investigation." Proceedings of 8th International LS-DYNA User's Conference, Dearborn, MI, May 2-4, 2004.
4. Melis, M.; Carney, K.; Gabrys, J.; Fasanella, E.; and Lyle, K.: "A Summary of the Space Shuttle Columbia Tragedy and the Use of LS-DYNA in the Accident Investigation and Return to Flight Efforts." Proceedings of 8th International LS-DYNA User's Conference, Dearborn, MI, May 2-4, 2004.
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6. Lyle, K.; Fasanella, E.; Melis, M.; Carney, K.; and Gabrys, J.: "Application of Non-Deterministic Methods to Assess Modeling Uncertainties for Reinforced Carbon-Carbon Debris Impacts." Proceedings of 8th International LS-DYNA User's Conference, Dearborn, MI, May 2-4, 2004.
7. Fasanella, E. L., Lyle, K. H., Gabrys, J., Melis, M., and Carney, K., "Test and Analysis Correlation of Foam Impact onto Space Shuttle Wing Leading Edge RCC Panel 8," Proceedings of 8th International LS-DYNA User's Conference, Dearborn, MI, May 2-4, 2004.

Table 1 Model Parameters

RCC Panels 10 & 11, T-Seal 11:

- RCC material properties: *Degraded, minimum-strength material*
- Material model: Developed at GRC using LS-Dyna Mat 58 (MAT_LAMINATED_COMPOSITE_FABRIC)

Foam:

- 2 x 7 x 11.88-in rectangular solid
- Weight: 0.23 lbs
- Impact velocity: 1000 ft/sec
- Material model: developed at GRC using LS-Dyna Mat 83 (MAT_FU_CHANG_FOAM, BX250RW01)

Simulation:

- *Contact_automatic_nodes_to_surface: foam to RCC
- *Contact_automatic_surface_to_surface: RCC to RCC
- MPP version 970 on Linux

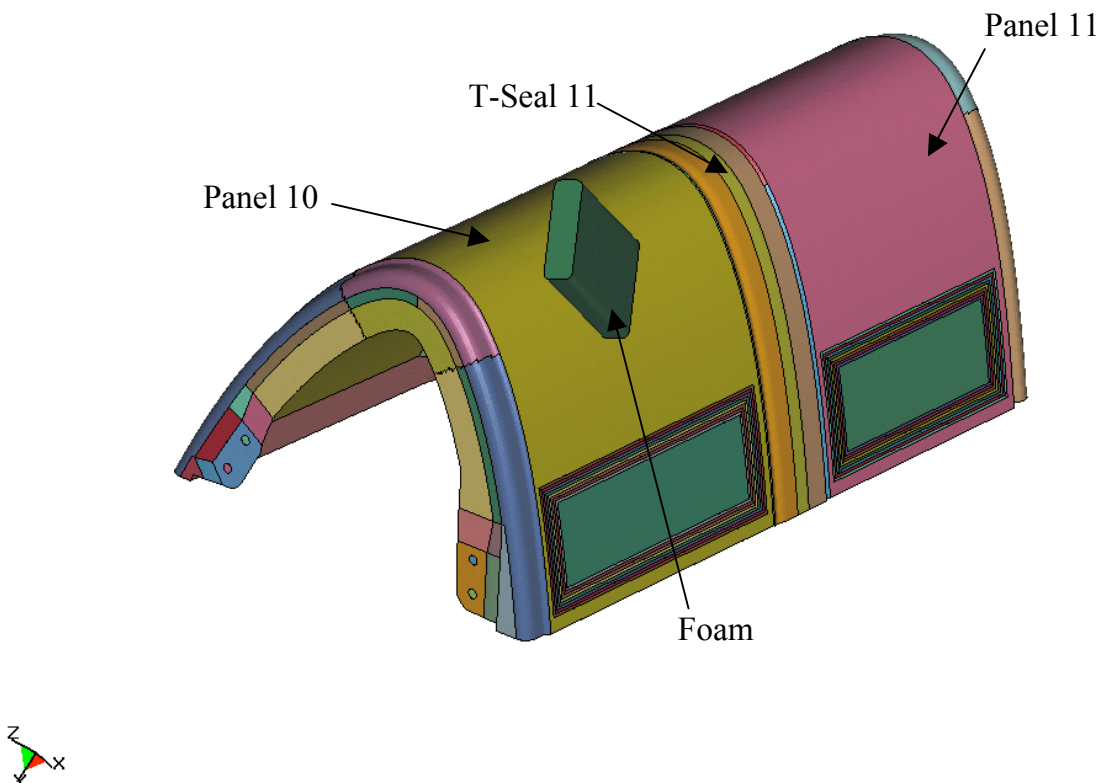
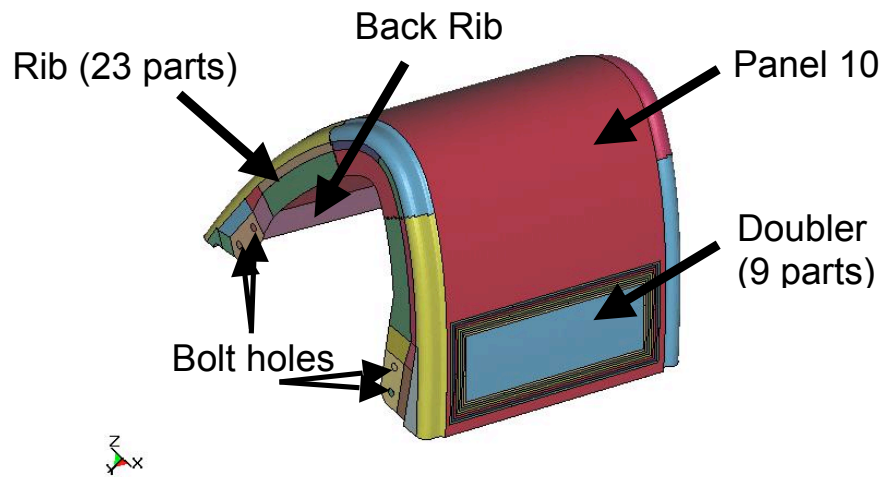


Figure 1 Baseline finite element model of Panels 10, 11 and T-Seal

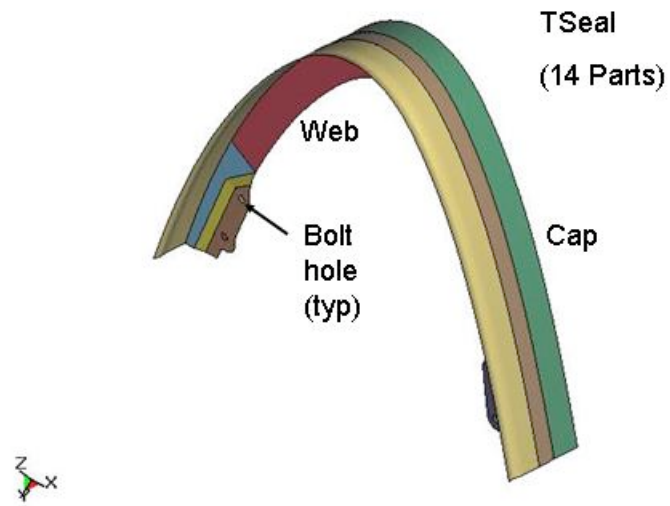


Figure 2 Finite element model discretization



(a) Panel with ribs

Figure 3 Typical Model Components



(b) T-Seal model

Figure 3 Typical Model Components (Concluded)

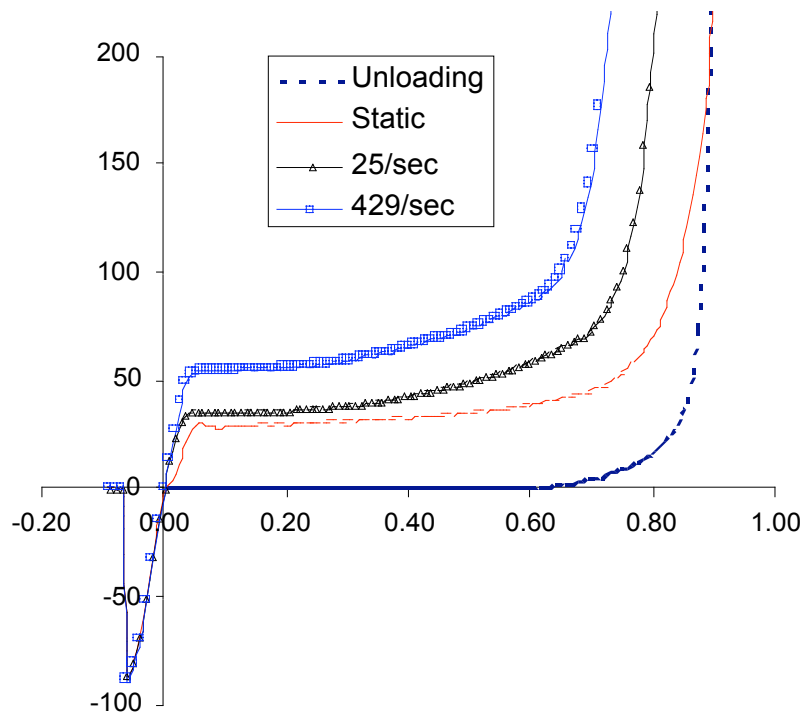


Figure 4 BX 250 foam stress strain curves used in MAT 83

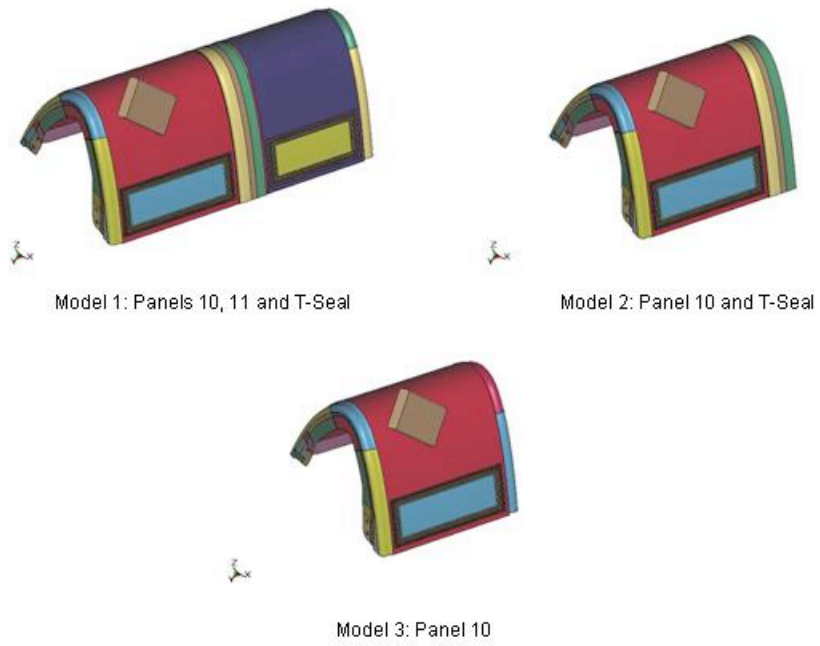


Figure 5 Simulation models with varying complexity

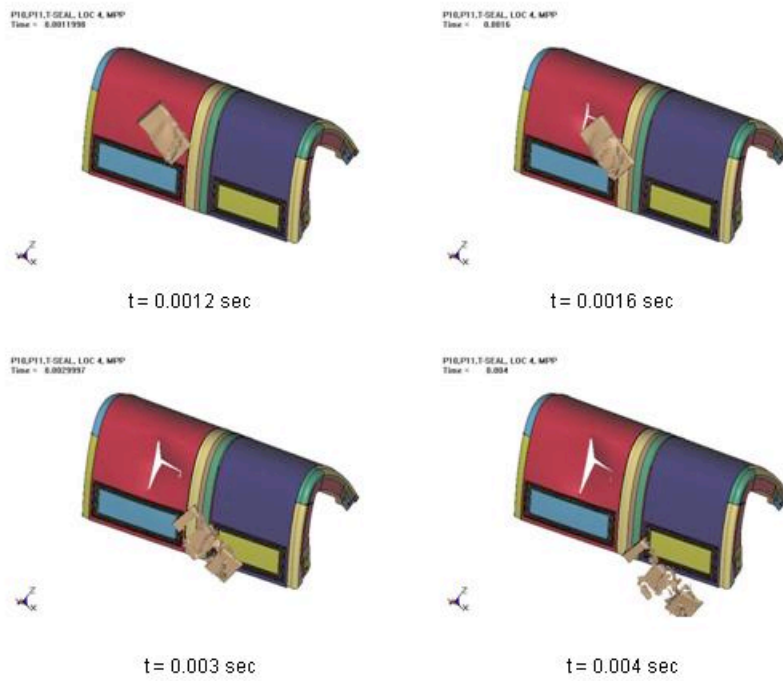


Figure 6 Deformation results for baseline simulation

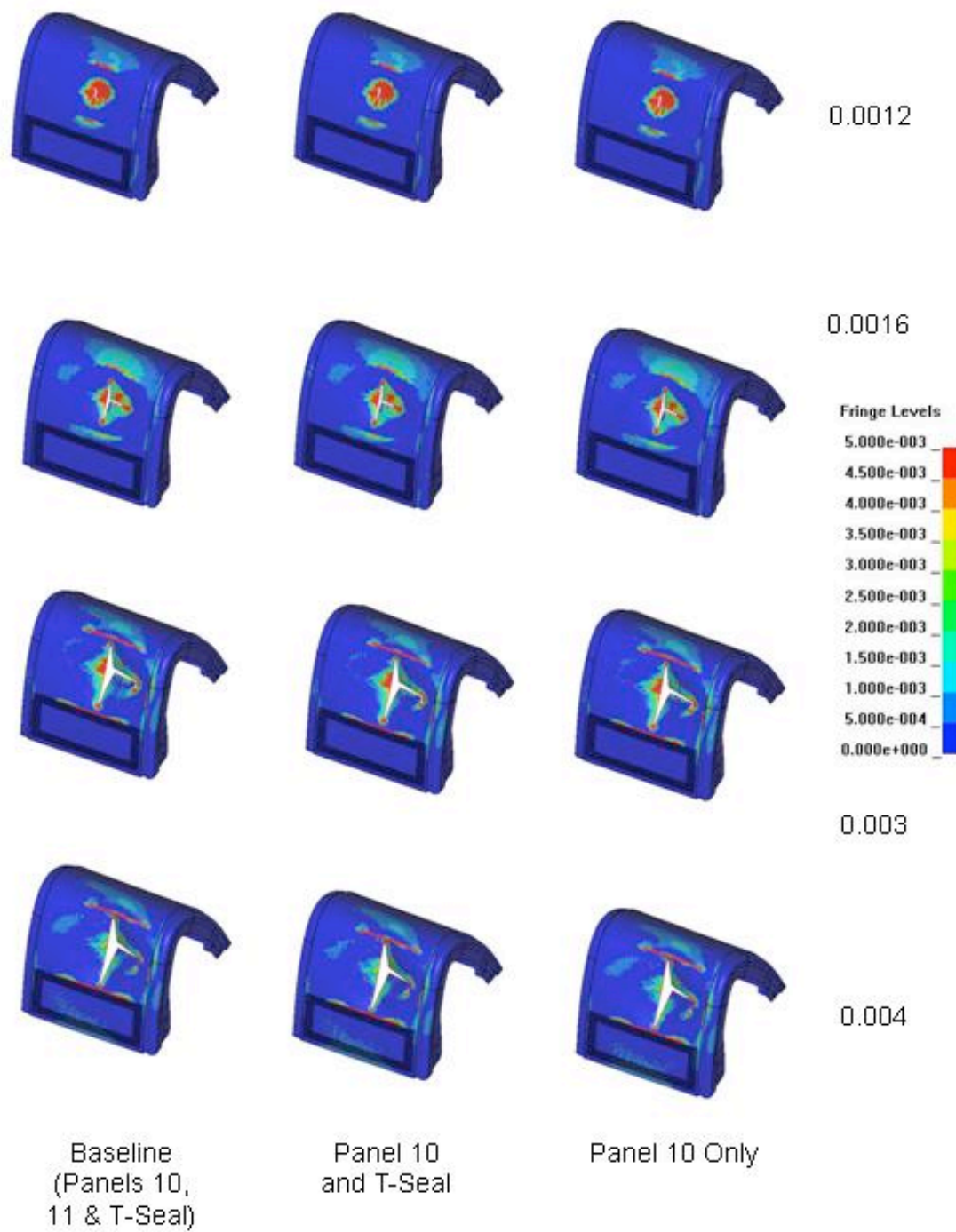
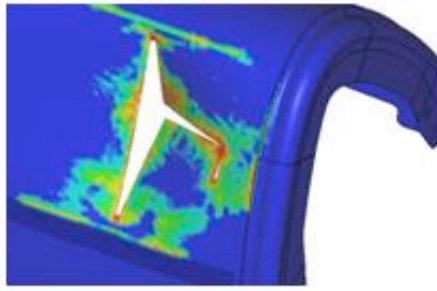
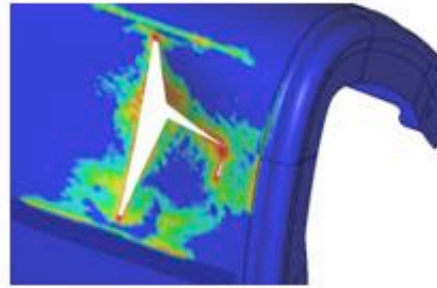


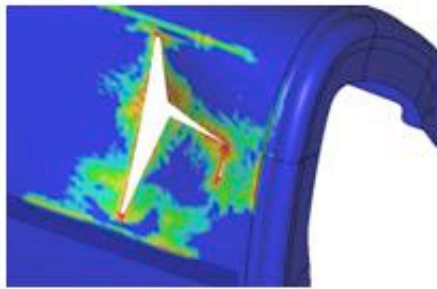
Figure 7 Comparison of maximum principal strain contours for three simulations



Baseline (Panels
10, 11 & T-Seal)



Panel 10
and T-Seal



Panel 10 Only

Fringe Levels

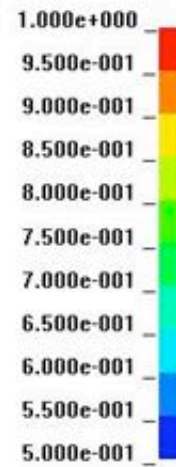


Figure 8 History variable 1 contours at end of simulation ($t = 0.004$ sec)

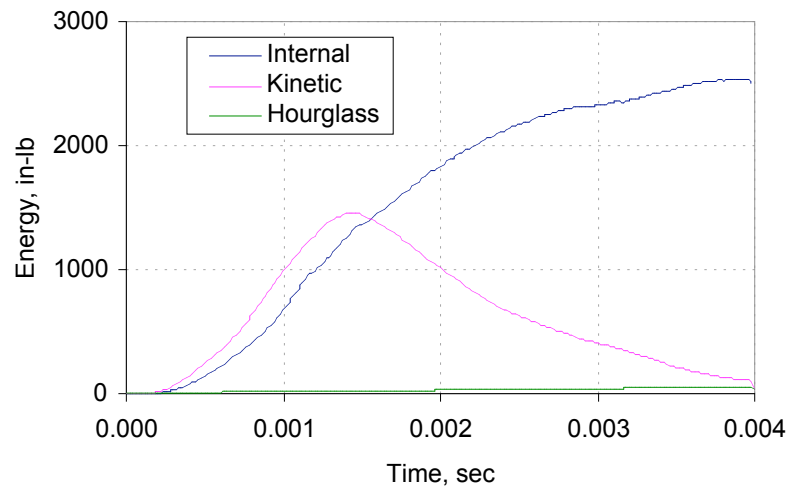


Figure 9 RCC (Panel and Rib) energies for Panel 10 only model

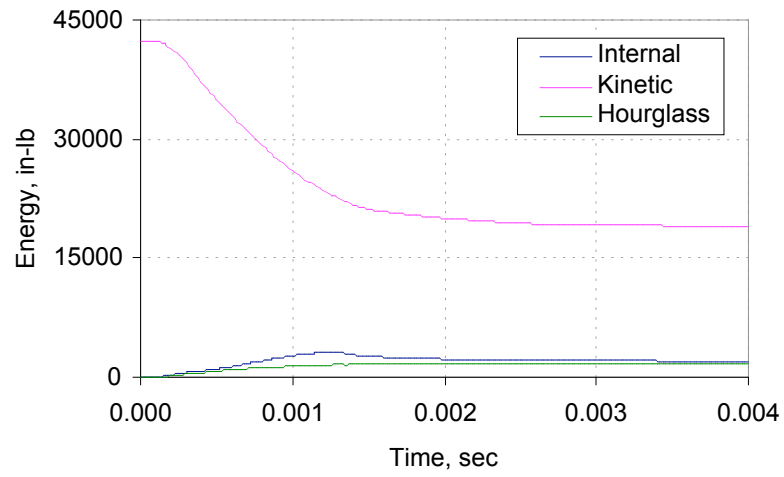


Figure 10 Foam energies, Panel 10 only model

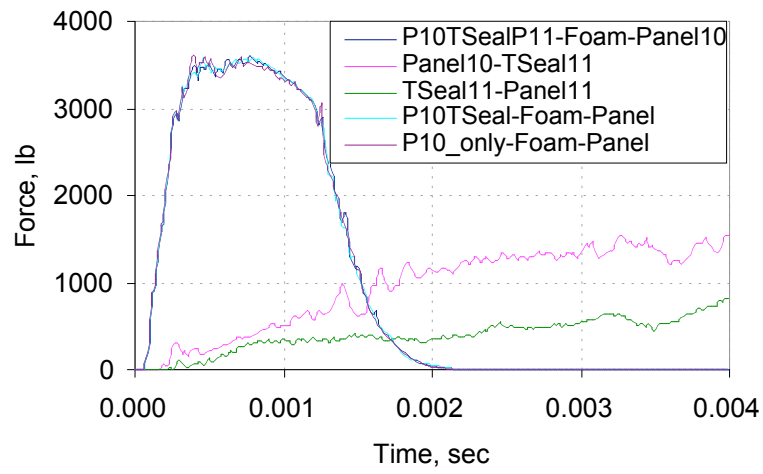


Figure 11 Contact forces for baseline model (Panel10, Panel 11 and T-Seal 11); note impulse = 4.2 lb-sec

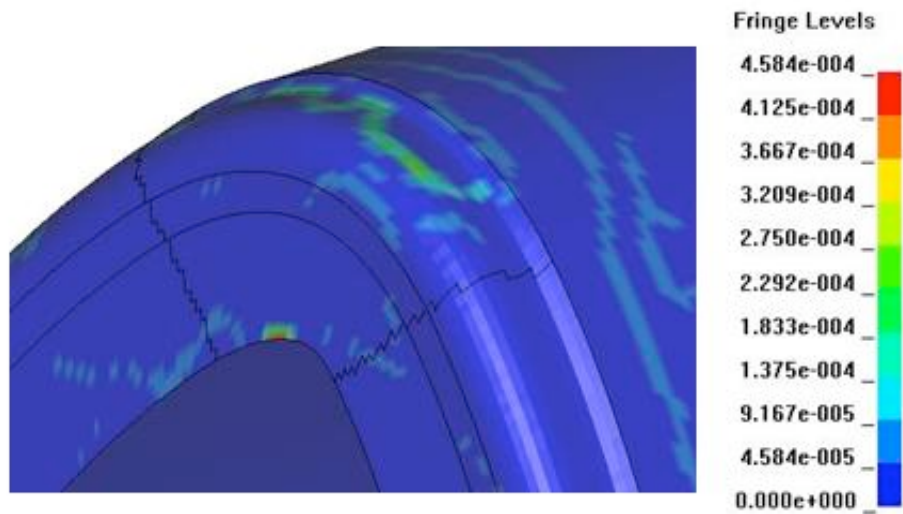


Figure 12 Maximum principal strain, Panel 11, baseline model

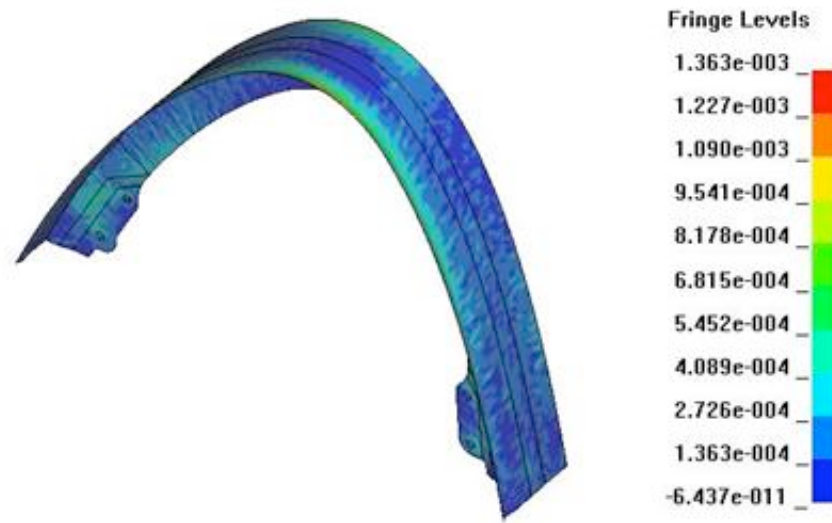


Figure 13 Maximum principal strain, T-Seal 11, baseline model

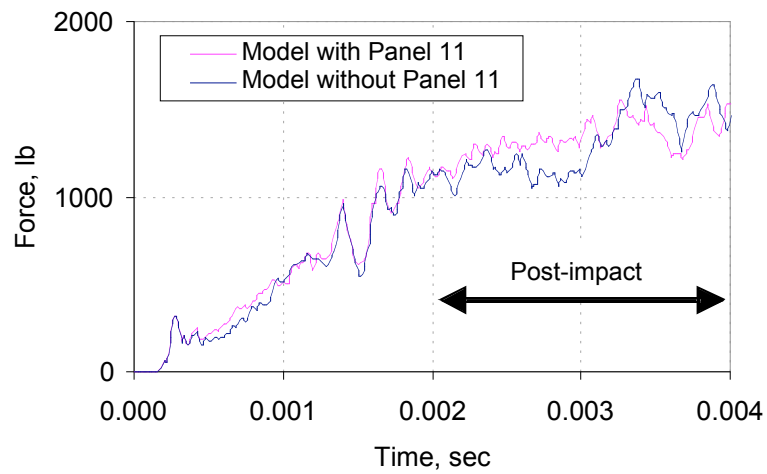


Figure 14 Comparison of contact force between Panel 10 and T-Seal 11 for models with and without Panel 11

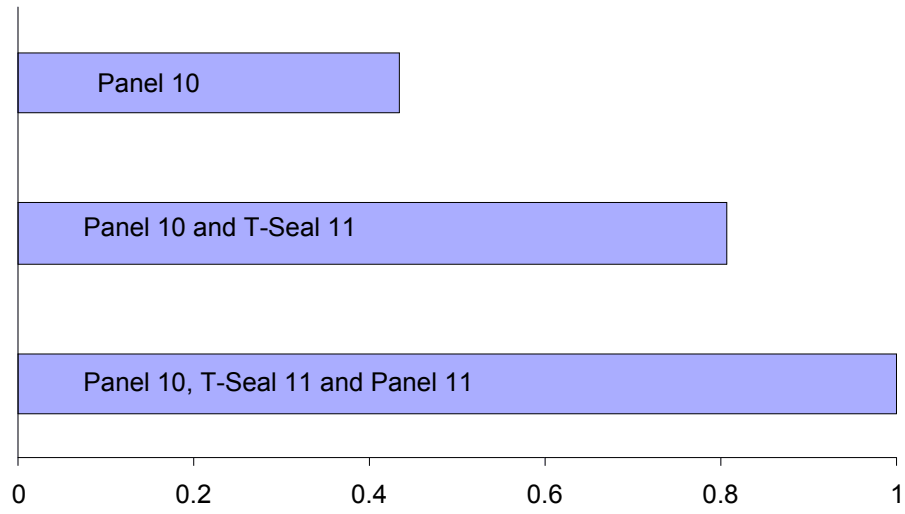


Figure 15 Relative computational effort for the three simulations

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